Large-Scale Physical Forcing of Thin Layer Dynamics

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LONG-TERM GOALS

My long-term goals are (1) to understand how physical processes influence the formation, maintenance and dispersion of thin layers of planktonic organisms, and using this information (2) to predict the temporal occurrence and spatial distribution of thin layers in the ocean.

OBJECTIVES

My objectives for this study were the following: (1) To work with Drs Holliday and Donaghay to deploy autonomous acoustical and optical instrumentation at eight coastal US sites, (2) to quantify the temporal occurrence and spatial distribution of thin planktonic layers at eight coastal US sites, (3) to assess the hydrography at each of the coastal sites in order to provide a physical context within which we may investigate thin planktonic layers, (4) to expand a database containing information on biological and physical processes related to thin layer dynamics, (5) to select an appropriate site for a future thin layers process study in an open-coast environment.

APPROACH

Background Information: My research team has played an essential role in the field of Thin Layers research over the past eight years. Our collective advances in optical and acoustical instrumentation, as well as in deployment techniques, have led to the discovery and quantification of thin layers of biological organisms in the sea. Thin layers range in thickness from a few centimeters to a few meters. These layers can extend horizontally for kilometers and persist for days (Dekshenieks et al. 2001, McManus et al. in press). Thin layers have significant impacts on the biological structure and dynamics of marine systems, as well as the optical and acoustical signatures in those systems. As a result, it is critical that we refine our ability to detect these structures, and develop the capability to predict the spatial distribution and temporal occurrence of these structures.

East Sound Washington: In 1996 and 1998 experiments funded by ONR Physical Oceanography and ONR Biological & Chemical Oceanography took place in East Sound, WA. During these experiments, an extensive series of physical and biological measurements were made to quantify the temporal and spatial scales of thin layers, and to investigate the physical mechanisms contributing to thin layer dynamics. As a result of this research we have made critical connections between physical processes and thin layer dynamics (Dekshenieks et al. 2001, McManus et al. submitted[a], McManus et al. in press). Our results show that regional-scale circulation patterns (e.g. buoyant plumes, episodic changes in water mass type) can have significant impacts on thin layer distribution. Our results also show that local hydrography plays a significant role in determining the spatial distribution [location (depth) and structure (thickness)] of thin layers. In addition, our results indicate that the Richardson number can be used as one of the indicators of the presence and/or absence of thin layers in the marine environment.

Exploration of Eight Coastal Ocean Sites: In 2001 and 2002 ONR Physical Oceanography and ONR Biological & Chemical Oceanography funded Drs. McManus, Holliday and Donaghay to deploy autonomous acoustical and optical instrumentation used to detect thin layers, and to conduct hydrographic assessments at eight coastal ocean sites around the US. In order to interpret patterns in biological distribution, it is necessary to understand the hydrography. Thus, before arriving at each coastal site, I developed preliminary descriptions of physical hydrography from the published literature. Second, I utilized satellite imagery to infer regional-scale circulation patterns. SeaWIFS was used for ocean color, and AVHRR was used for sea surface temperature. Once at the coastal site, I assessed the local hydrography. At most sites, a small vessel was equipped with an RD Instruments downward-looking 1200 kHz ADCP and a SeaBird SBE-25 CTD. Wind and tidal time-series were available at all sites from NDBC data buoys and NOAA tide gauges. Information from the literature reviews, satellite imagery and hydrographic assessments provide a physical context within which we may investigate thin planktonic layers. *Instrumentation deployed at each coastal site:* Dr. Holliday deployed one Tracor Acoustical Profiling System (TAPS-6), an upward looking 600 kHz ADCP and a thermistor chain with 1 m vertical resolution. At many of the sites Dr. Donaghay deployed one autonomous underwater winch profiler equipped with a SeaBird SBE-25 CTD and a Wet LABS Inc. ac-9. Data packets from the TAPS-6 and the autonomous underwater winch profiler were telemetered to shore, recorded and processed in real time. The deployed instrumentation functioned autonomously for a period of two to three weeks at each site.

WORK COMPLETED

(1) We have deployed autonomous acoustical and/or optical instrumentation at eight coastal sites to quantify the temporal occurrence and spatial distribution of thin planktonic layers. Thin planktonic layers were observed at six of the eight sites (Appendix A). (2) I have assessed the hydrography at each of the eight coastal sites and have provided a physical context within which we are investigating thin planktonic layers. (3) We have analyzed each thin layer in detail and related the known biological properties of the layer to physical processes acting on the layer. (4) My graduate student and I are expanding a database containing information on biological and physical processes related to thin layer dynamics. (5) I have written and/or contributed to eight publications resulting from this work in the past two years (Dekshenieks et al. 2001, Alldredge et al. 2002, Rines et al. 2002, Storlazzi et al. 2003, Holliday et al. 2003, McManus et al. in press, McManus et al submitted[a,b]).

RESULTS

The results from the coastal ocean sites are consistent with our conceptual model of thin layer occurrence and distribution from East Sound. There are strong statistical relationships between thin layers and physical structure at all coastal ocean sites. In addition, the Richardson number can be used as one of the indicators of thin layer presence and/or absence in the coastal ocean. These results demonstrate that thin layers can not only develop in open coastal systems (such as Monterey Bay (McManus et al. submitted[a])) but that they can become just as intense and persistent as they are in semi-enclosed waters of coastal fjords (such as East Sound (McManus et al. in press)). The strong statistical relationships between thin layers and physical structure indicates that we cannot understand thin layer dynamics without first understanding physical oceanographic processes.

East Sound, Washington: *Physical Environment:* East Sound is a small fjord on Orcas Island within the San Juan Islands, WA (48° 39N, 122° 53W). Hydrography: Circulation patterns in East Sound are influenced by wind and tidal forcing. On a regional scale, circulation patterns are also affected by buoyant plumes from the Fraser River. Bathymetry: East Sound has steeply sloping topography characteristic of a fjord. The western mouth of the Sound is partially obstructed by a 12 m sill. Otherwise; the Sound has a mean depth of 30 m. Wind: During the summer months, winds are from the south ~80% of the time and from the north ~20% of the time, with average wind speeds of 3.5 m/s.

Tide: Tides in East Sound are mixed; however, they are predominantly semidiurnal. The tidal range varies from a 0.31 m to 3.5 m. Freshwater: East Sound and Orcas Island experience low precipitation (49 cm/yr). Freshwater inputs in the region are predominantly from the Fraser River, located 40 km to the North of the Sound. *Thin Layers:* Thin phytoplankton layers were observed and measured in 54% of our profiles. Over 71% of all thin layers were located at the base of, or within the pycnocline. The fact that these layers ranged in thickness from 0.12 m to 3.61 m, with 80% of all thin layers measuring < 2 m in thickness, indicates that conventional sampling methods would underestimate both the intensity and abundance of thin layers. Thin layers in East Sound occur over a broad range of buoyancy frequency and shear. Our results also indicate that there are physical conditions under which thin layers do not occur, e.g. where the water column is turbulent ($Ri < 0.25$). Thus, we do not expect persistent thin layers in tidally mixed regions, nor do we expect thin layers in wind mixed surface layers (Dekshenieks et al. 2001, McManus et al. in press, McManus et al. submitted[b]).

Monterey Bay, California: *Physical Environment:* Monterey Bay is located on the central coast of California (36° 56.05N, 131° 55.52W). Hydrography: Circulation patterns within Monterey Bay are influenced by coastal upwelling, wind forcing, tidal forcing, and local heating (Breaker and Broenkow 1994). Bathymetry: The Monterey Submarine Canyon (MSC) is the major topographic feature in Monterey Bay. The MSC divides the Bay into northern and southern sections. Wind: In general, winds are from the northwest (upwelling favorable) between May and October and from the southeast between November and April. Tide: Tides in Monterey Bay are mixed, however they are predominantly semi-diurnal, with a maximum range of 1.6 m. Freshwater: Average precipitation varies spatially, from approximately 150 cm/yr in the northern end of the Bay, to 48 cm/yr in the southern end of the Bay. *Thin Layers:* Thin layers of zooplankton, phytoplankton, bioluminescence, bacteria and viruses were observed in Monterey Bay. Concentrations in these layers were 3 to 5 times higher than those above or below the layer. Layers ranged in thickness from 10 cm to 2 m, and layers of zooplankton and phytoplankton were observed to persist for days. Acoustic records indicate a dynamic complex of zooplankton layers, moving vertically at periods of 4-20 minutes over depth ranges of 2-8 m. The position of these thin zooplankton layers are being modulated by internal waves (McManus et al. submitted[a]).

Santa Barbara, California*: Physical Environment*: Our initial study site was located in Goleta Bay in the Santa Barbara Channel (34^o 24.26N, 119^o 47.10W). During the first 3 weeks of the study we observed sub-mm and mm size bubbles interfering with the TAPS signal. These bubbles resulted from methane from local seeps. Although the acoustic examination of these bubbles is of interest in it's own right, the bubbles severely hindered visibility for our thin layers study. After 3 weeks, we re-deployed our instrumentation southeast of the original location (34^o 23.96N, 119^o 46.54W). <u>Hydrography:</u> The large-scale circulation patterns of the region are dominated by the equator-ward flowing California Current (CC), and the pole-ward flowing Southern California Countercurrent (SCC). Coastal upwelling in this location is weaker than the rest of the California coast. <u>Bathymetry:</u> Both sites had gently sloping bottom topography. <u>Wind:</u> Maximum alongshore winds occur during the spring (~3.9 m/s). <u>Tide:</u> Tides are semi-diurnal, with a maximum tidal range of 1.8 m. <u>Freshwater:</u> With the exception of minor river inputs there are no significant freshwater sources to this area. *Thin Layers:* Thin Layers in the Santa Barbara Channel differed from layers measured in East Sound and Monterey Bay; (1) zooplankton biomass was low during both deployments, (2) thin layers measured 2-4 m in thickness (greater in vertical dimension than East Sound and Monterey Bay), (3) night-time vertical migrations were also reduced significantly, and (4) the layers were comprised of one size of organism (i.e. layers were segregated by size and depth).

Oceanside, California: *Physical Environment:* Oceanside is located on the Pacific coast within a region known as the Southern California Bight (SCB) (33^o 17.45N, 117^o 30.82W). <u>Hydrography:</u> The large-scale circulation patterns are influenced by the equator-ward flowing California Current (CC), and the pole-ward flowing Southern California Countercurrent (SCC). <u>Bathymetry:</u> Oceanside has gently sloping topography and a long, linear coastline. <u>Wind:</u> Maximum alongshore winds occur during the spring (~4.02 m/s). <u>Tide:</u> Tides are semi-diurnal, with a maximum tidal range of 2m (Souza and Pineda 2000). <u>Freshwater:</u> With the exception of minor riverine inflows, there are no significant freshwater sources to the Oceanside area. *Thin layers:* Thin layers of zooplankton were observed periodically at Oceanside during the 3-week period that the TAPS was deployed. Nighttime vertical migrations were significantly enhanced at this site; zooplankton biovolumes increased at dusk each day and decreased again at dawn.

Destin, Florida: *Physical Environment:* The Destin site was located 3.2 km offshore in the northern Gulf of Mexico (30^o 23N, 86^o 30W). <u>Hydrography:</u> The dominant physical processes influencing physical structure at this site include wind forcing, freshwater input and eddies from the Loop Current. <u>Bathymetry:</u> This site has a gently sloping shelf. <u>Winds:</u> Winds average 3.7 m/s. This region experiences strong wind forcing during the fall hurricane season (Oey 1995). <u>Tides:</u> Tides are diurnal with an average tidal range of 0.7 m. <u>Freshwater Input:</u> The primary source of fresh water is from the Mississippi River, the Choctawhatchee River and surrounding creeks, with the greatest input during spring. *Thin Layers*: Thin layers of zooplankton were observed periodically at the Destin site during the 3-week period that the TAPS was deployed.

Charleston, South Carolina: *Physical Environment:* Charleston Harbor is a 1,200 square mile estuarine environment located along the southeastern coast of the United States (32^o 45N, 79^o 52W). <u>Hydrography:</u> The circulation patterns within the harbor are dominated by wind forcing and freshwater inflow. <u>Bathymetry:</u> The Charleston Harbor estuary has a soft mud basin, which averages 12 m in depth at low tide. <u>Winds:</u> Wind speeds vary between 2-5 m/s and are generally from the southwest during the spring and summer and are from the northwest during fall and winter. Tides: The tide is predominantly semi-diurnal. The tidal range varies from 1.1 to 2.0 m (Althausen and Kjerfve 1992). Freshwater Input: The Cooper River is the primary source of freshwater input with an annual contribution of 110 m^3/s (Pinckney and Dustan 1990). Rainfall averages 52 cm/yr. *Thin Layers:* Thin layers of zooplankton were observed on one day during the 3-week period that the TAPS was deployed at the Charleston site.

Strawberry Hill, Oregon: *Physical Environment:* The Strawberry Hill site was located 3.3 km off the coast of Oregon, 49 km south of Newport OR (44^o 15.22N, 124^o 7.59W). Hydrography: Circulation patterns near Strawberry Hill are dominated by the equatorward flowing California Current, wind forcing and tidal forcing. Bathymetry: The Strawberry Hill Site was located on a gently sloping shelf. Wind: Winds are predominantly from the north during the spring and summer months, and from the south during the fall and winter months. Tide: Tides in this region are semi-diurnal, with a tidal range of 0.31 to 3.3 m. Freshwater: The Oregon coastal region experiences heavy precipitation (183 cm/yr). Oregon coastal waters also receive significant freshwater inputs from the Columbia River (Smith et al. 2001). *Thin Layers:* No thin layers were observed at the Strawberry Hill site during our August 2002 deployment due to a widespread hypoxic event. In July of 2002 an extraordinary expanse of water with almost no dissolved oxygen had developed close to the Oregon coastline. Vertically, the hypoxic water spread from the bed to 10 to 20 m off the ocean floor. Horizontally, the region of hypoxic water extended 55 km south of Newport OR, and 10 km offshore. By August the low oxygen zone was found in water as shallow as 10 m, just beyond the breaking waves. The widespread effects of this hypoxic event were not discovered until late August 2002 (i.e. after our deployment).

Pensacola, Florida: *Physical Environment:* The Pensacola site was located 8 km off Pensacola Beach in the northern Gulf of Mexico (30^o 28.18N, 87^o 11.98W). Hydrography: The dominant physical processes influencing the hydrography include wind forcing, freshwater input and eddies from the Loop Current. Bathymetry: Pensacola has a low relief shoreline and gently sloping continental shelf. Wind: The annual mean wind speed is ~6.0 m/s. Pensacola experiences strong wind forcing during the fall hurricane season. Tide: Tides are diurnal with an average tidal range of 0.7 m. Freshwater: Pensacola Bay is the major source of freshwater to the site. *Thin Layers:* Thin layers were not observed at the Pensacola site. During the 2-week study in the fall of 2001, the water column was well mixed ($Ri < 0.25$). This resulted from increased wind velocities resulting from the passage of a tropical depression. As previously indicated, we would not expect persistent thin layers in well-mixed, unstratified regions.

Summary: Thin layers were not observed at Strawberry Hill, OR due to a widespread hypoxic event. Clearly, in order to have thin layers of planktonic organisms, there must be a seed population. In addition, thin layers were not observed at Pensacola FL. During our study in Pensacola the water column was well mixed due to the passage of a tropical depression. These results agree with our ealier results from East Sound which show that thin layers do not occur when the water column is turbulent ($Ri < 0.25$). It is highly likely that Strawberry Hill and Pensacola can support thin layer development under oxygenated conditions and reduced wind conditions, respectively. Of the remaining six sites, the thinnest layers (~0.6 m), with the greatest intensity (a_p440 ~14 m^{-1}), and longest duration (~14 d) were observed in Monterey Bay, CA, and East Sound, WA. Monterey Bay is an open embayment, while East Sound is a well-protected coastal fjord. ***Based on the information from the coastal ocean site explorations, the most appropriate open-coast environment for a future thin layers process study is Monterey Bay, CA.***

IMPACT/APPLICATIONS

The work described here: (1) Transitions the thin layers program, in a timely fashion, to study thin layers in an open coast environment; (2) Allows us to identify a suitable site in the coastal ocean where a future process study of thin layers may occur; (3) Augments and compliments the current development of autonomous underwater winch profilers with high resolution sensors (physical, optical, biological and chemical) capable of detecting thin layers; and (4) Supports a currently funded ONR project designed to utilize bio-acoustical instrumentation to explore several coastal ocean sites for the occurrence of thin acoustical layers.

RELATED PROJECTS

Related projects include:

(1) Ocean Response Coastal Analysis System (ORCAS), Donaghay (PI) McManus (CoPI), funded by NOPP.

(2) Development of Advanced Technology for Sensing Zooplankton, Holliday (PI), funded by ONR code 322.

(3) Plankton Patch Feasibility Experiments, Donaghay (PI), funded by ONR code 322.

(4) Finescale Processes in the Plankton: Physical and Biological Linkages, Cowles (PI), funded by ONR code 322.

(5) Interactions of Small-Scale Physical Mixing Processes with the Structure, Morphology, Bloom Dynamics and Optics of Non-Spheroid Phytoplankton, Rines (PI) Donaghay (CoPI), funded ONR code 322.

(6) Fine-Scale Nutrient Gradients and Thin Plankton Layers in Coastal Waters, Hanson (PI), funded ONR code 322.

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PUBLICATIONS (Please note PI formerly Dekshenieks)

In the past two years, I have written and/or contributed to eight publications resulting from this work.

Alldredge AL, TJ Cowles, S MacIntyre, JEB Rines, PL Donaghay, CF Greenlaw, DV Holliday, MM **Dekshenieks**, JM Sullivan and JRV Zaneveld. **2002**. Occurrence and mechanism of formation of a dramatic thin layer of marine snow in a shallow Pacific fjord. Marine Ecology Progress Series. 233: 1-12.

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Appendix A:
Coastal ocean site location, presence/absence of thin layers, and composition of organisms in the thin layers.

	Coastal Site	Presence	Composition
1	East Sound WA	yes	phytoplankton, zooplankton, bioluminescent organisms, bacteria, marine snow
2	Monterey Bay CA	yes	phytoplankton, zooplankton, bioluminescent organisms, bacteria, viruses
3	Santa Barbara CA	yes	zooplankton
4	Oceanside CA	yes	zooplankton
5	Destin FL	yes	zooplankton
6	Charleston SC	yes	zooplankton
7	Strawberry Hill OR	no	
8	Pensacola FL	no	